Introduction to Semiconductor Devices
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Lecture - 6.1
Schottky Barrier in Metal-Semiconductor Junction

Hello everyone welcome back. So, in the last week, we were looking at the behavior of p-n junctions. And we understood the electrostatics and how the current flows in a p-n junction and various non-idealities. So, today, we would like to introduce different type of a junction which is very important.

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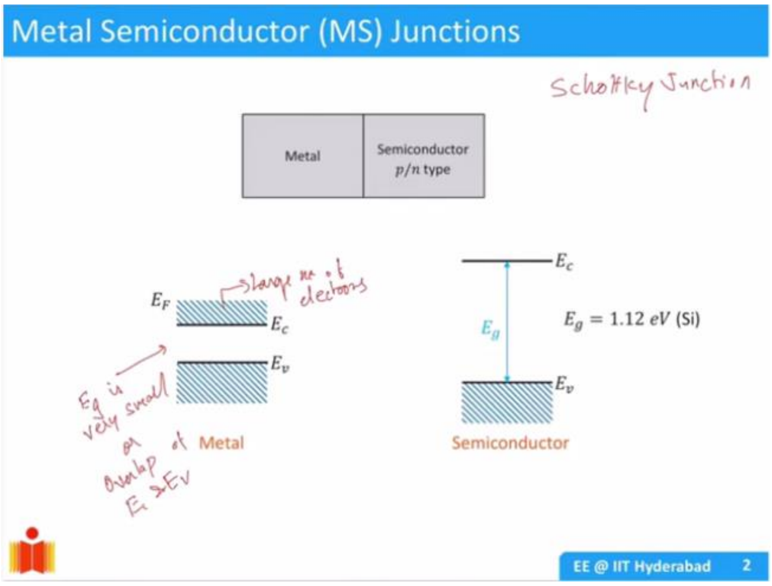

Metal Semiconductor (MS) Junctions

Schottky Junction

The junction is between a metal and a semiconductor. So, in the previous case, we have taken a p type semiconductor, n type semiconductor and we have understood what happens. Now, we would like to replace one of the semiconductors with a metal. And we can look at the interface between the metal and a p type semiconductor or an n type semiconductor. So, what happens in that scenario?

So, these types of junctions are also known as Schottky junctions. Or, you could also call it as Schottky diode. We will see how the diode behavior comes out. So, based on our understanding of materials so far, what do we expect when we have an interface between or a junction between a metal and a semiconductor? So, we have the valence band and the conduction band.

And then there is a Fermi level which depends on the doping density. What happens in a metal? We know even in a metal there is going to be bands. But in case of metals, this E g is very small. This is one of the scenarios when the metals band gap is very small or you could also have or overlap of E c and E v.

So, essentially the conduction band comes into the valence band so that effectively you have a large number of electrons in the conduction band in the outermost band. That is a characteristic of a metal. So, because of presence of large number of electrons they are very good conductors. So, now, what happens when we bring these materials together?

How can we analyze it? So, to do that, we need to introduce a few more concepts, so, definitions rather.

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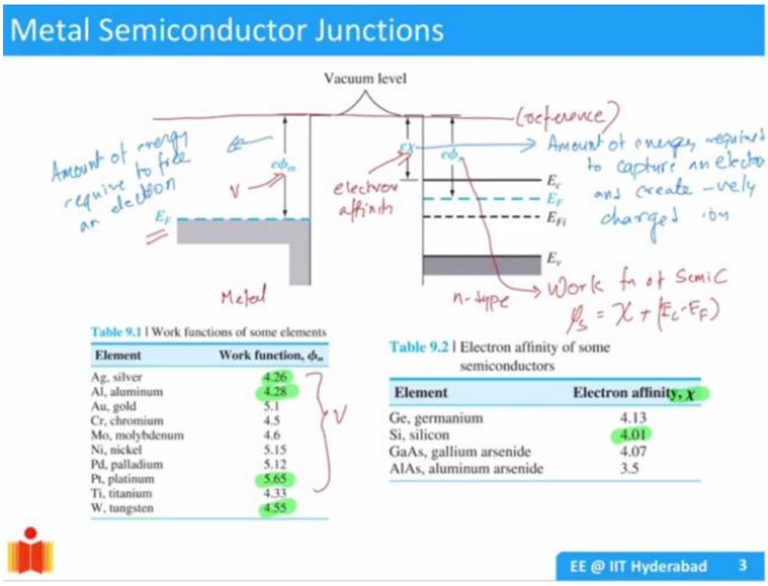

Metal Semiconductor Junctions

Table 9.1 | Work functions of some elements

Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Table 9.2 | Electron affinity of some semiconductors

Element	Electron affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

So, this is essentially how you know the bands will look like. Let us say there are 2 materials which are separate. They are not yet in connection. They are separate. So, if they are separate, the metal is going to have a Fermi level. And there is a parameter which we call as a work function of a metal. That determines how much energy is required to take an electron from the metal to outside the metal.

We can refer to that energy level as a vacuum level typically. This is essentially a vacuum level. This is a reference level. So, the electron is essentially free of the atom, it is this it can freely move about. So, that is the reference level. If you want to take out an electron from the metal into the vacuum level, the energy reference is known as the work function.

Work function is represented in terms of voltage φm. So, charge times the volts will be E v. So, various metals have you know different work functions. They are not uniform. For example, here in the table, you see that work functions are in the range of about you know 4.26 is the smallest and sinker.

And then the largest is 5.65 platinum. So, you could also have a few other elements like magnesium and thing which have even smaller work functions. So, the metals have a range of work functions typically in the range of 4 to 5. The important ones are aluminum which we use routinely in semiconductor industry. And we also use tungsten sometimes and a few other materials of course.

So, these the units here are in volts, so, charge times that will give you the energy. This is work function of a material. And there is nothing much we can do about this. When you deposit aluminum, we get certain work function.

It also depends on the deposition conditions and so on. So, for example, if I deposit aluminum in 2 different chambers with 2 different techniques. The other variable or other parameter that we want to define is known as electron affinity.

So, electron affinity essentially is defined for a semiconductor here. And the electron affinity is a measure of how much energy is required to capture an electron and convert the semiconductor into a negatively charged ion. And in the bands, you can show electron affinity as basically this amount of energy required to capture an electron and create a negatively charged ion.

Whereas, work function was amount of energy required to free an electron. So, essentially in semiconductor, electron can be present in a conduction band. So, if you can capture an energy electron from the vacuum level into the conduction band that is enough. So, that is the electron affinity Chi is the symbol. And this is also known for a material.

Crystal crystalline silicon will have an electron affinity of 4.01. And other materials have different numbers. For example, gallium arsenide has 4.07. And let us say 4.1 for germanium and so on. We can define a work function for a semiconductor, because semiconductor also has a certain Fermi energy.

And then you can remove an electron from vacuum level. So, the work function of a semiconductor φs is going to be:

$$\varphi s = Chi + (Ec - Ef)$$

This is an n type. So, the work function of a semiconductor is not a fixed number but it would depend on the extent of doping that we have in a semiconductor whereas the electron affinity is fixed.

Once you have silicon the electron affinity is always going to be 4.01. So, now, this is when the semiconductor the metal and the semiconductor are far apart. They are independent. Now, if they are brought in contact, what happens? There are no dust or surface scattering and all that.

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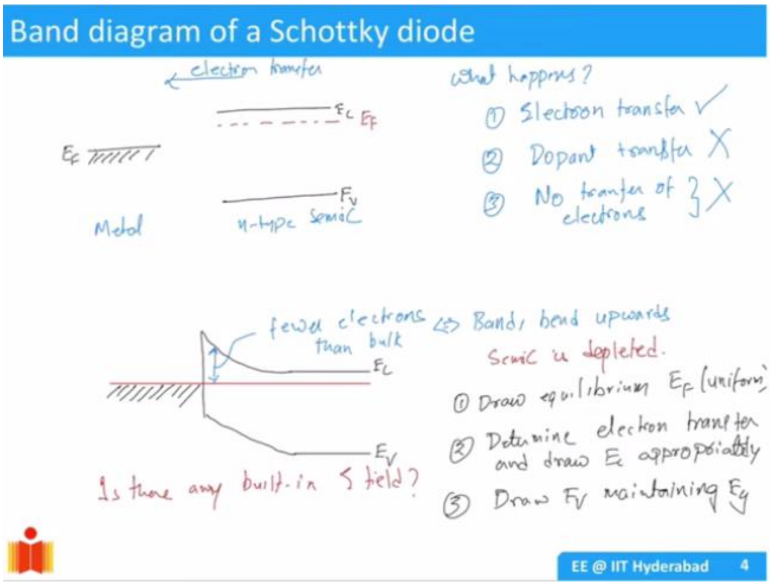

Band diagram of a Schottky diode

What happens?
① Electron transfer ✓
② Dopant transfer ✗
③ No transfer of electrons } ✗

⇔ Bands bend upwards
Semic is depleted.

Is there any built-in ξ field?

① Draw equilibrium E_F (uniform)
② Determine electron transfer and draw E_c appropriately
③ Draw E_V maintaining E_g

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To understand that we would like to draw, a band diagram. Fermi energy of a metal E F. And we are taking a semiconductor is an n-type semiconductor. So, I will take E v and E c. And I will also draw an E F.

Semiconductor into contact, what happens? Well, the Fermi level is essentially a measure of the energy level at which the probability of finding an electron is half. So, essentially to that level you could think of as energy electrons being there at T equal to 0. If temperature is higher, it is going to smear out. That smearing out is given by the Fermi function. So, essentially you could think of it like a water level.

So, water in a tank that analogy we can use. So, now, what happens is the Fermi energy of the semiconductor is higher. So, there are more electrons there and on the other side the electron energy is lesser. There can be an electron transfer. Will there be any hole transfer? There are no holes here.

The majority carriers are electrons, at a much higher energy and there are a few holes. So, electron transfer is going to be dominant mechanism.

Electron transfer from semiconductor to the metal because semiconductors Fermi level is higher. Will there be dopant transfer? No, there is not going to be any dopant transfer because dopants are essentially the fixed ions.

Whenever you are doping semiconductor, we are replacing a silicon atom with an n type semiconductor. It is going to be phosphorus or arsenic. If it is a p type, it will be boron. But these are fixed to the lattice. The dopants are fixed to the lattice. They cannot be transferred. Well, is it possible that there is no energy no transfer of electrons?

It is not because we have Fermi energy difference. Electron transfer happens from semiconductor to metal. Will it make any difference to the Fermi energy? At equilibrium, we have studied that in a device the semiconductor the Fermi level has to be uniform.

So, to draw the band diagram for a metal semiconductor (Schottky diode), we will take the Fermi level to be uniform and metal there are like lots of electron so it won't be changing. What happens to the semiconductor? Away from the junction between metal and semiconductor it is bulk semiconductor.

It is not going to be changing its properties. So, away from the junction you need to have the conduction band and valence band similar to the separated case. But as you approach the junction, what happens? We have taken some electrons from the semiconductor and then transferred them to the metal. Because of that, there are going to be some dopant atoms which become space charge. So, this is an n-type semiconductor.

If you remove an electron, you will be left with a positive charge. So, you are essentially removing the electrons. So, because of that, what happens is the electron concentration reduces at the interface. How do we represent a reducing electron concentration? The Fermi energy is going to be away from E c.

So, basically here the distance is large. So, fewer number electrons than bulk, because electrons have gone into the metal. That is why the bands are bending upwards.

Semiconductor is depleted. What happens to E v? It will not bend because we know that band gap cannot change. Your E v will be parallel. Ec and Ev are going to be in contact.

- Draw equilibrium Fermi level, equilibrium E F which is uniform across this device because there is no external bias. When you apply external bias, it is going to changing.
- Look at you know electron transfer. Determine electron transfer and check if it is an accumulation or a depletion and draw E c appropriately.
- Then draw E v maintaining E g.

Once you do this, this is the Fermi, so, this is a band diagram of a Schottky junction.
Is there any built-in electric field?

There is definitely, because there is a certain gradient in the E c. That is indicative of an electric field present in the device.

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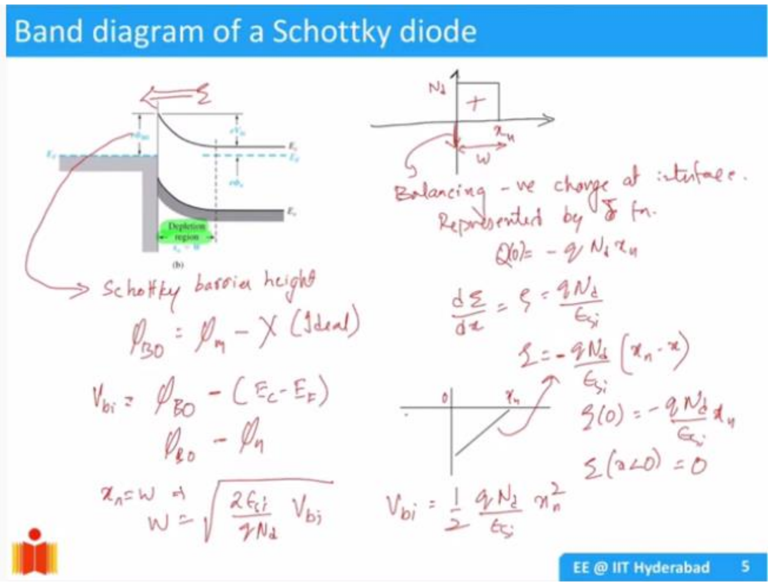

Band diagram of a Schottky diode

Schottky barrier height

$$\phi_{B0} = \phi_m - \chi \text{ (Ideal)}$$

$$V_{bi} = \phi_{B0} - (E_C - E_F)$$

$$\phi_{B0} - \phi_n$$

$$x_n = W \Rightarrow W = \sqrt{\frac{2\epsilon_{si}}{qN_d} V_{bi}}$$

Balancing -ve charge at interface.
Represented by δ fn.

$$Q(0) = -qN_d x_n$$

$$\frac{d\mathcal{E}}{dx} = \rho = \frac{qN_d}{\epsilon_{si}}$$

$$\mathcal{E} = -\frac{qN_d}{\epsilon_{si}}(x_n - x)$$

$$\mathcal{E}(0) = -\frac{qN_d}{\epsilon_{si}} x_n$$

$$\mathcal{E}(x<0) = 0$$

$$V_{bi} = \frac{1}{2}\frac{qN_d}{\epsilon_{si}} x_n^2$$

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Depletion region is indicated in the above attached slide in green. This depletion region is because the dopant atoms are uncovered in that region. And we will also define its height. It is an important parameter which is called as Schottky barrier height.

Why is it a barrier? Well, you have electrons in the semiconductor and the field is pointing out in this direction. So, electrons cannot cross that field. Electrons experience the barrier. Electrons cannot move into the metal. Similarly, metal electrons cannot come into the semiconductor. So, there is a barrier for that. And the height of the barrier is given by φbo. So,

$$\varphi bo = \varphi m - Chi$$

We have the Schottky barrier height. Electrons cannot easily travel across the barrier. Whenever there is an electric field there is going to be a built-in potential.

What is the built-in potential?
The first step is always to draw the space charge because once you know the charge you know Gauss law. Then you can determine the electric field. How is the space charge going to look like? In this case, well, we said that electrons are removed from semiconductors. So, they should acquire a positive charge.

And that is going to be a uniform semiconductor we have assumed. So, this is going to be N d. And this is going to be let us say some x n. The depletion region has extended the distance of x n. You could also call it the width of the depletion region. The crucial difference from a metal semiconductor junction and the regular p-n junction is that the balancing charge this is positive charge here.

The balancing charge is going to be occurring at the interface itself and it is like a delta function. This is your balancing negative charge at interface. And it is like you know it is a delta function essentially represented by delta function. Why is it a delta function? Well, it is a metal. So, there cannot be any electric field in the metal because the charges will rearrange and then they will neutralize the electric field.

Electric field the moment you get into the metal it has to be 0. So, the difference in electric field is the surface charge. And that surface charge is effectively this.

So, for now, we said that there is a balancing charge.

$$Q(0) = -qNdxn$$

Charge distribution you are going to have electric field:

$$\frac{dE}{dx} = \rho = \frac{qNd}{\varepsilon si}$$

$$E(Electric\ Field) = \rho = -\frac{qNd}{\varepsilon si}(xn - x0)$$

At E(0) what you see is there is a sudden jump here.

$$E(0) = -\frac{qNd}{\varepsilon si}xn$$

$$E(x < 0) = 0$$

So, that difference is going to be given by the surface charge or delta charge whatever you have at the interface because of the boundary conditions. With electric field you can calculate the built-in potential. Built-in potential is going integral of electric field.

$$Vbi = \frac{1}{2}\frac{qNd}{\varepsilon si}xn^2$$

So, there is going to be band bending. And the bending of E c at 0 and at the bulk is going to be this difference built-in potential. And built-in potential can be given as:

$$Vbi = \varphi bo - (Ec - Ef)$$

$$Vbi = \varphi bo - \varphi n$$

φn is essentially the distance between the E c and E v. Built-in potential is quadratically dependent on the x.

$$xn = w(depletion\ width) = \sqrt{\frac{2 * \varepsilon si * Vbi}{qNd}}$$

What happens when you apply certain voltage?

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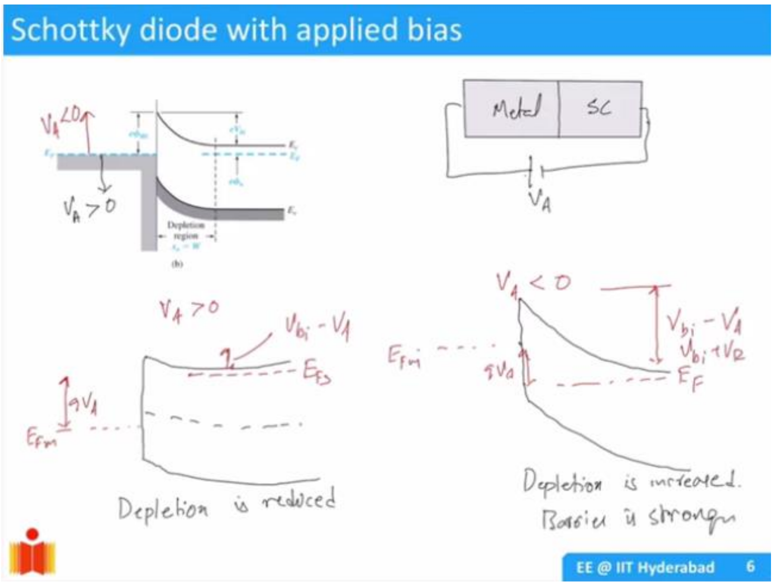

Schottky diode with applied bias

When V A is positive. This is metal, semiconductor and metal junction.

And you are applying with respect to the semiconductor you are applying a positive voltage to the metal. So, when V A is positive, Fermi level lowers. V A is greater than 0. When V A is less than zero, the Fermi level is going to go up. So, in a way, you could think of you know keep the E F in the bulk of the semiconductor as constant. Or, you know you hold it fixed and then move the E F in the metal.

If you are applying positive voltage, the whole band diagrams have to move down. I will draw the Fermi level in the semiconductor E F. And then I will pull the metal Fermi level lower by the extent of the applied voltage. So, this is going to be my q V applied. This is going to be E F S metal.

So, the barrier height is going to reduce. So, instead of previous case, you will have a barrier which is like this. Because we are pulling it down, we are essentially reducing the depletion. So, depletion is reduced because we are pulling down the Fermi level of the metal.

Another way to think about it is essentially we are putting positive charge on the metal. So, that is going to pull electrons towards the interface and so the number of electrons increases in the semiconductor. So, you have the Fermi the bands going down. So, this is what happens when you have positive voltage. This is for V A greater than 0. So, essentially the barrier is lowering if your V A is less than 0, the reverse happens.

We draw the E F semiconductor. And then let us take the E F of metal to be somewhere E F of metal to be higher. So, now, we are applying upon negative voltage. So, in a way, you are repelling the electrons from the junction. You are not helping that process of electrons at the junction.

So, what happens now is you will have the barrier which is stronger like this. Depletion is increased now. Barrier is stronger or rather built-in potential is stronger. Va is applied forward bias and Vr is reverse bias.

$$Vbi - Va;\ Va > 0; \quad Barrier \downarrow$$

$$Vbi + Vr;\ Vr < 0; \quad Barrier \uparrow$$

So, this is how the bands will change.